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THE RÔLE OF POSSIBLE EUTECTICS IN ROCK MAGMAS.

THE appearance of Professional Paper No. 18, *The Chemical Composition of Igneous Rocks, Expressed by Means of Diagrams*, by Professor Iddings, completes a trilogy of works¹ which will leave a permanent impression upon the nomenclature and progress of petrography. No one who has not done a little work of the sort can begin to conceive of the amount of labor employed in the comparatively small paper of less than one hundred pages which has just appeared. And even so, it is probable that vastly more in the way of experiment in trying to group the facts in different arrangements has been done, of which no trace remains. We see the finished railroad survey, and can form some conception of the engineering, but we cannot know how many lines may have been run through the dense forests before settling upon the final track.

It is easy also to notice possible improvements in the track when it is once completed; and if I make some suggestions along this line, it is only with the greatest respect for the distinguished authors of the new chemical classification. Whatever modifications the future may have in store, I think that there will be much of their work which will endure, and that such terms as "persalic" and "dofemic" will after a little become household words to the petrographers of all countries. I think the remark of Mr. Iddings, that we must look upon a rock as the chemist looks upon a solidified mass of mixed salts, that "we must think of the study of igneous rocks, their magmas and relationships, as purely physico-chemical problems, involving the measurement and comparison of mass and force, and their definite quantitative expression," as one of very great importance. When he goes on to say that there are no recognizable groupings of

¹ *The Quantitative Classification of Igneous Rocks*, by CROSS, IDDIGS, PIRSSON, AND WASHINGTON, and Professional Paper No. 14 by WASHINGTON, being the two previous works.

rocks or noticeable subdivisions of chemical series, that chemically similar rocks occur in genetically different families, that it follows that the subdivisions of all igneous rocks into groups for the purpose of classification must be on arbitrarily chosen lines, and that it is no argument against a classification if a rock of great importance belongs on the boundary of a classificatory division, that any system of classification will be as natural as any other system, he is rather too pessimistic. Merely as a mass of mixed salts, there are certain common relationships which hold, and of which any system of classification, the new one included, must take account. He has pointed out a number of such facts: (1) In the great majority of rocks alkalis do not exist in excess of that required to make feldspar or nephelite; (2) The commonest rocks are in composition like the average of all rocks which has the silica percentage of 58.7 to 59.77 and an alkali-silica ratio of 0.083 to 0.088. Iddings, in fact, suggests the possibility that all rocks have been derived from one common magma by splitting. If so, this splitting must have gone on under chemical and physical laws which are to be traced and followed in the classification. There is, however, another possibility which I wish to suggest, namely, that in the process of splitting there is a tendency in one of the fractions toward that same common average.¹ To this point we will return later. There are numerous other facts which Iddings points out, such as the inverse relation between silica and alkalis, and iron and magnesia, and various other notes on pp. 19, 64, 65, 70-81, of which any classification may take account, as, in fact, the new one does, to a very large degree. Upon that depends its serviceability. The fact that there are exceptions does not invalidate the importance of this relation, provided they are not too many.

Now, if one looks over the general diagram, Plate I, which Iddings has prepared to see that it is true that there is "no clustering of analyses" and "no natural subdivisions" (p. 17), I cannot agree with him in the conclusion he draws. In the first place,

¹This would fit especially well in a planetesimal theory; in fact, would be almost necessary in view of the wide prevalence of basaltic magmas.

as he himself has pointed out, there are no more alkalis in most rocks than alumina and silica to go with them. In the second place, there are very few rocks with high silica percentage down about to the point representing the average rock in which the ratio of alkali-silica is less than 0.04. As the amount of alkalis increases, the number of analyses becomes more numerous. Somewhere between the ratios 0.08 to 0.09 they are most abundant. After that they diminish somewhat and become less up to a ratio between 0.12 and 0.16, and then they become more numerous once more. If we suppose this not to be accidental, we must assume *a tendency on the part of a certain group of magmas toward an alkali-silica ratio between 0.08 and 0.09*. I fixed on 0.083 from the diagram. This, I noted, was the ratio of the average rock. Expressing this in fractions, the alkali-silica ratio would be 1:12. This suggested to me at once a combination of orthoclase or albite and quartz with equal molecular proportions of silica. This again reminded me of Rosenbusch's spherulite-forming microfelsite, which he supposes to be of the composition $K_2O \cdot Al_2O_3 \cdot x SiO_2$, with x greater than 6. It is also the composition of micropegmatite where the quartz and feldspar are equal. All these facts harmonize with the supposition that the combination $(Na_2O, K_2O) \cdot Al_2O_3 \cdot 6SiO_2 + 6SiO_2$ is the eutectic ratio of alkali and silica. If such magmas are composed mainly of alkalis, alumina, and silica, these will tend to crystallize out whichever of these components happens to be in excess, and the analyst will be likely in the long run to obtain more analyses near this ratio than either above or below. This supposition is obviously compatible with the idea that the igneous rocks are derived from fusion either of pre-existing sedimentaries or of planetesimals.

We have remarked that down to where silica equals 0.59 and 0.57 there seems to be a belt of analyses having about this ratio, with comparatively few as the ratio dropped. Now, of course, these rocks are not all simply feldspar and quartz. How do we explain this belt or line? Simply by supposing that this eutectic relation holds, even though other elements were combined with the silica, that the 6 silica may be more or

less in combination with other elements commonly occurring in rocks, and yet that the eutectic ratio of alkali:silica :: 1:12 would hold true. Possibly it must be in combination with H_2O or some other oxide.

The first element, of course, to be considered would be the lime. What composition of albite and anorthite would give the same eutectic ratio? A little simple algebra proves that it is the commonest labradorite ($Ab_2 An_3$). Now, this feldspar is, as we all know, one of the commonest in rocks, and more easily fusible than either albite¹ or anorthite, so that it is strictly eutectic. In other words, the diagram seems to show that there is probably a eutectic series from a micropegmatite with quartz about equal to albite or orthoclase down to labradorite. If this theory is true, then there would be a tendency in rocks where the alkali-silica ratio was less than 1:12 to have the silica crystallize out first in a porphyritic way as quartz; and, on the other hand, if the alkali ratio were a little greater, there might be a tendency to have the feldspar crystallize out early, so as to bring the residual magma down to the eutectic ratio. A large excess of alkali would bring it near another eutectic. Corresponding to these would be a more or less quartzose marginal zone where the crystallization first began. That this is liable to be modified more or less by irregular changes in temperature, pressure, and environment, I need hardly add.

But what about the other elements, in particular the iron and magnesia? If silica were there in excess of the eutectic ratio, they would combine with it very easily and, such compounds being relatively insoluble in the magma, crystallize and separate out, in sharp form embedded in the eutectic compound. In harmony with this, we find some of the few analyses which are markedly below the eutectic ratio containing considerable quantities of lime, magnesia, and iron. They may be aggregates of these earlier eliminations of the magma—divergent splits. Some of them are such, I judge from the description. Moreover, the minerals formed in such magmas must have high silica ratios, be augite or enstatite rather than olivine.

¹ According to the latest researches of Doelter and others this is not so—for albite is 10° to 15° more fusible.

We have remarked that the eutectic ratio continues in a line from micropegmatite to labradorite ($Ab_2 An_3$). This feldspar has a silica percentage of 53 and an alkali-silica ratio of 1:12. This is so close to the ratios of the average rock that they are within the limits of the probable error; in fact, we may say that the average rock has the same silica percentage and alkali ratio as labradorite. Now, we will notice upon the chart that once the silica falls below this ratio there is marked change in the behavior of the analyses, and they seem to stream off toward the lower right-hand corner, the alkali ratio dropping with the silica ratio. We might infer, therefore, that for rocks less silicious the eutectic ratio above given did not hold; or, rather, it may hold, so far as the alkalis are concerned, that they still find the most fusible compound $Na_2O \cdot Al_2O_3 \cdot 6 SiO_2$, and $6 RO SiO_2$, but that in the presence of an excess of bases there is some other equally or more fusible compound $RO SiO_2$.

This, remember, is a purely theoretic inference from laws of chemistry and Iddings's diagram. A moment's thought shows how amply it is confirmed by petrographic research. This more fusible mineral is augite. As the percentage of SiO_2 in augite is about the same as in labradorite (between 55 and 44), and cannot anywhere in the pyroxene group get above that of enstatite (60), we see why the distribution of analyses turns a square corner, and we find them quite frequently from 0.58 SiO_2 down with all kinds of alkali ratios. We may go on to ask if there is any eutectic balance between labradorite and augite. As the ratios of lime to silica and percentage of silica are practically the same in the augite and in the labradorite series, the question as to the predominance of the one or the other tendency will probably be a question of balance mainly between the femic and alkaline constituents. The femic constituents in a magma mainly of felsitic eutectic are only slightly soluble and tend to crystallize out early as magnetite, biotite, hornblende, etc., even though present in very small quantities; and even though they increase markedly in abundance, their solubility or fusibility is still small, except as they can be taken into the augite molecule. An excess of magnetite or olivine crystallizes readily.¹ The metallurgists tell us

¹I am neglecting a lot of minor matters.

about this in their slag formulæ. Consequently, it is *a priori* probable that labradorite and augite magmas mix readily and without tendency to split; though, when they actually come to crystallize, petrographic observation teaches that the labradorite feldspar is the earlier and the augite later for the rocks on the right or lower silica side of the average rock. The reverse is true on the other side. We must remember that, so far as chemical affinities allow, the eutectic (most fusible, least solidified) magma will contain a little of every element going; and therefore we are not surprised at the complexity of the composition of the augites which are collected in the table accompanying the statement of the *Quantitative System*. The latest researches show that basaltic magmas are fusible at distinctly lower temperatures than either labradorite or augite.

Nor are we surprised that, if we draw a line from the average rock-analysis point, or that for labradorite, in the average direction in which the less silicious and less alkaline analyses diverge therefrom, it will strike the line of no alkalis at 43 per cent. SiO_2 , or somewhat less; for this is not only the lowest silica percentage which augite, diallage, and the feldspar series reaches (anorthite), but the maximum for olivine.

So in the femic magmas there is a clear tendency away from extremely different percentages of iron, lime, or magnesia. Probably the ratio $\text{CaO} : \text{MgO} : \text{FeO} :: 2 : 1 : 1$ is not far from the eutectic one. In the following group of analyses from Lighthouse Point, for instance, it is clear that at the center, where there was opportunity for differentiation and adjustment of the magma, and the eutectic would accumulate, there is more lime than at the quickly chilled and cooled contact. The magma had an excess of magnesia and iron for eutectic relations, and this is shown petrographically by an early generation of olivine and magnetite.

Returning to the Iddings's diagrams, it seems, from a study of the distribution of Class I, that a few rocks are included (anorthosites, canadases) which it goes against the grain to include—rocks with an unusual amount of lime, but really tributary to the femic eutectic; that the real natural family is from

ANALYSES OF STONE FROM LIGHTHOUSE POINT, UNDER DIRECTION OF
E. D. CAMPBELL, BY E. E. WARE, JUNE 30, 1903.

DISTANCE FROM MARGIN	CONTACT		616 mm (2.2 feet)		4,115 mm (13.5 feet)		7,600 mm (24.9 feet)	
	No. 1	Mole- cule	No. 3	Mole- cule	No. 6	Mole- cule	No. 8	Mole- cule
SiO ₂	46.08	0.783	47.67	0.795	47.25	0.787	47.10	0.785
Al ₂ O ₃	17.85	0.175	17.55	0.172	18.00	0.176	17.47	0.172
Fe ₂ O ₃	3.13	0.019	2.51	0.016	2.21	0.014	2.66	0.017
FeO	10.30	0.143	12.59	0.175	12.42	0.172	12.93	0.179
MgO	(a) 7.10	0.177	5.65	0.141	6.35	0.159	6.88	0.172
CaO	(a) 8.47	0.152	10.75	0.192	11.45	0.204	10.27	0.183
Sodium oxide	2.04	0.033	2.21	0.035	1.96	0.031	1.91	0.031
Potassium oxide	0.60	0.006	0.65	0.007	0.66	0.007	0.59	0.006
{ H ₂ O at above 800° C.	(b) 1.97	0.168	0.35	0.112	.....	.....	.....	.....
{ H ₂ O at 110° C.	(a) 1.55	0.086	0.40	0.028	.....	.....	.....	.....
CO ₂	0.20	0.005	0.18	0.004	.....	.....	.....	.....
P ₂ O ₅	0.143	0.001	0.169	0.001	0.158	0.001	0.161	0.001
S	0.097	0.003	0.183	0.0057	0.086	0.0027	0.111	0.003
Cl	0.07	0.002	0.05	0.0014	0.02	0.0006	0.09	0.0025
MnO	0.26	0.003	0.19	0.003	0.18	0.003	0.15	0.002
	100.760		101.102		100.744		100.322	
Ratio, alkalis: SiO ₂	0.048		0.053		0.0483		0.0472	
Ratio, pore space: solid space, in gasolene	0.0473		0.0012		0.0032		0.0018	
Sp. Gr. in gasolene	2.83		3.02		3.01		3.02	

(a) Checked later in another sample.

(b) Determined on new sample, first method incorrect.

labradorose as a limit up; and that those which occur with more than 30 per cent. of magma belonging to the femic eutectic are rare.

Moreover, it will be noted that there is among the orders between orders 4 and 5 a new principle of classification introduced. This corresponds approximately to the extra alkaline eutectics. Similarly, the rockallases appear very isolated and strange in the salemic family.

I shall not, however, pretend to discuss the analcitic, melilitic, and other alkaline eutectic magmas, with which Iddings is much better acquainted than I. My object is rather to suggest that ultimately a more rational and natural, and therefore useful, classification of analyses might be attained if our main magmatic groups were defined by the eutectic within whose influence they come, so that in splitting one part will be nearer the eutectic and the other farther from it. I have Iddings's diagram to thank for this suggestion.

I am not going to say all that might be said about such intergrowths as perthite and sigterite (nepheline-albite), and other pegmatitic intergrowths as keys to eutectic proportions, because I do not wish to write a treatise, but rather a review—I fear too long—pointing out what seems to me inferences to be drawn from Iddings's diagrams. But the loss of mineralizers might change the eutectic. For instance, if the eutectic be $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 + 6\text{SiO}_2 + 6\text{H}_2\text{O} \cdot \text{SiO}_2$, a loss of H_2O might mean the replacement of the H_2O by $\frac{1}{2}(\text{CaO} \cdot \text{Al}_2\text{O}_3)$ which might be a chemical quantitative change entirely worthy of recognition in a quantitative chemical classification, *if* it proved of sufficient importance; as much so as any magmatic split.

I think that the indications of Iddings's diagrams are that it is not from a quantitative chemical standpoint of primary importance, although his figures take no account of the water. It is not to be forgotten that in a holocrystalline rock the H_2O of the magma, while it may be in combination in biotite, analcite, etc., is very likely to be concentrated in drusic and microdrusic cavities, and not be noticed in the analyses at all, or, if at all, then in the water given off below 110° ; but a maximum idea of this quantity may, however, be derived from the porosity, which in the dike mentioned above is for the more crystalline part less than a third of 1 per cent.

While, therefore, Iddings's diagrams do suggest a natural grouping and classification based on the various eutectics of various magmas, yet the time is not yet ripe for such a permanent arrangement. We do not know enough about the eutectics. In the meantime, the new system of pigeon holes has some advantages, and many, especially of the minor groups, may endure.

Still we can see that the old divisions of rocks might be grouped around the average rock and given a more precise chemical meaning, as follows:

1. Acid, *i. e.*, alkali-silica ratio 0.013 —, and silica percentage 0.58 +, or limited as in diagram, eutectic ratio toward which crystallization takes place, alkali : SiO_2 : : 1 : 12.

Granites and diorites, and many syenites.

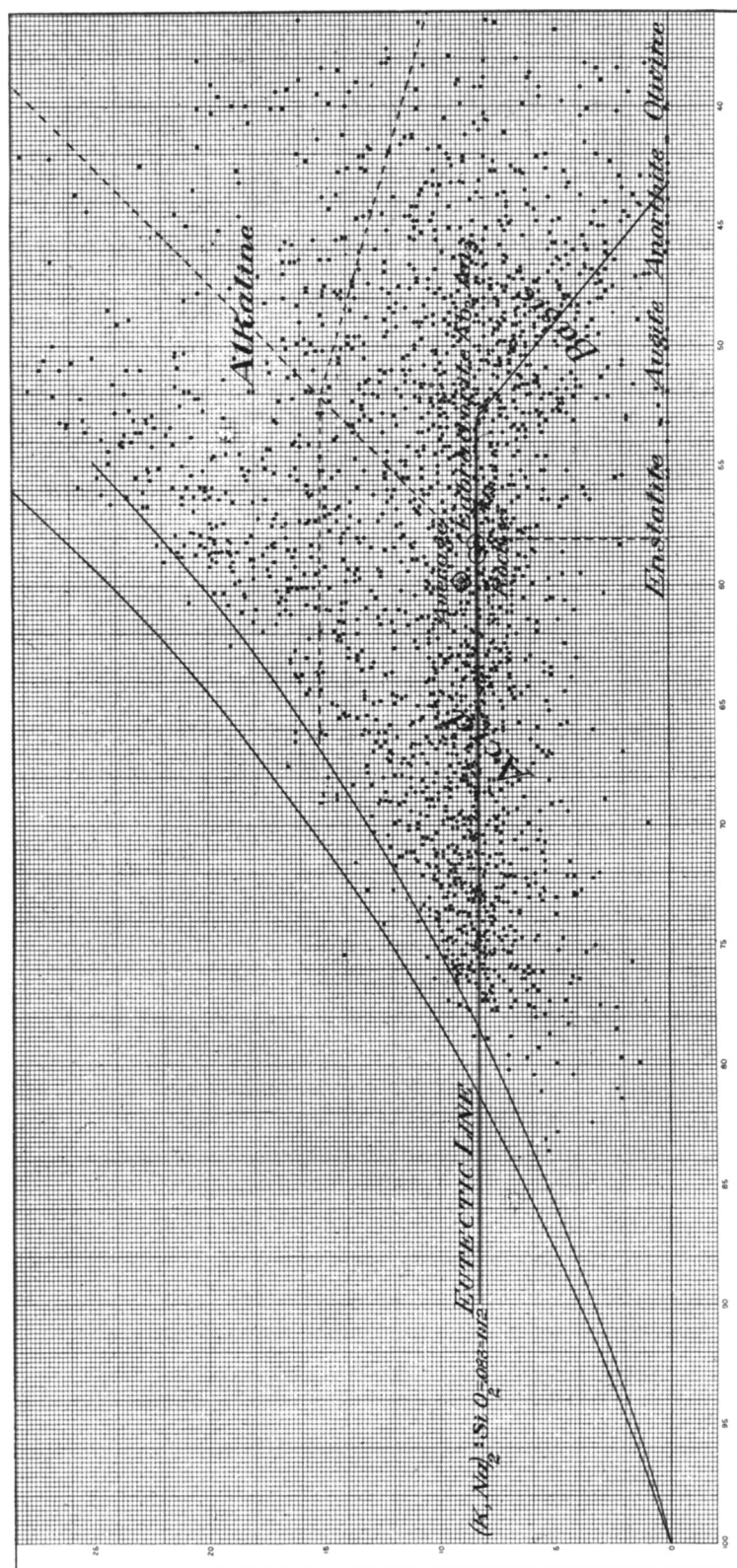


Diagram modified from Iddings's Plate I to show the natural clustering along the main eutectic line, and the possibility of a natural quantitative chemical classification of the igneous rocks.

The general rules for computing the norm of a rock can be simplified if made applicable only to this division.

2. Basic. Silica percentage, 0.58—, bounded, as shown on diagram perhaps, or by some other line expressing the fact that the eutectic is not melilite, but augite. Eutectic ratio, Ca : (Mg : Fe) : SiO₂ :: 1 : 1 : 2.

Basalts, gabbros, peridotites, etc. Computing the place of such rocks in a quantitative system is quite simple. All the alumina can be combined with potash, soda, and sufficient lime and counted salic, everything else femic, so that the ratio sal : fem is quickly found, and the ratio of soda to potash and alkalis to lime are found incidentally.

3. Alkaline. All other rocks, which obviously should also be subdivided, perhaps, as shown in the diagram, into a femic and salic group, and farther yet.

What ought to be done is carefully to study the whole field, with due regard to magmatic splitting, watching the last crystallization, and determine as nearly as may be what are the eutectic ratios in the silicate magmas. Then the work should be experimentally verified, in the new geological laboratory that I hope we are to have. Then, finally, we shall no longer have to envy the metallographist,¹ who measures the areas of micropegmatite (eutectic) copper and copper oxide, and areas of solid copper, and says: "So much eutectic with 3.45 per cent. Cu₂O, and so much plain copper: there must be just so much copper and so much oxygen."

In such study it is the last-formed minerals, with a little of nearly everything in their molecule, which show by their composition the eutectic proportions of the different constituents.

Since writing the above I have noticed in the *Beilage Band XVII* of the *Neues Jahrbuch*, p. 516, and especially pp. 546-64, an article by Schweig, and in the *Centralblatt*, 1903, p. 605, a note by Linck on a series of experiments exactly along the line

¹ HOFMAN, GREEN, AND YERXA, "A Laboratory Study of the Stages in the Refining of Copper," *Transactions of the American Institute of Mining Engineers*, October, 1903.

suggested, and in part only confirmatory of the suggestions above. For instance, Linck (pp. 606, 607) found a magma with 49.05 SiO_2 and an alkali silica ratio of 0.115, after absorbing all the silica it could at 1300°C . change to a magma with 52.20 SiO_2 and an alkali silica ratio of 0.082, almost precisely on the supposed eutectic line. Another with 62.62 per cent. silica absorbed a mixture of ferrous and ferric iron until the silica percentage dropped to 60.58 and the magma could be nearly expressed as $(\text{NaK})_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6 \text{SiO}_2 + \frac{1}{2} \text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2 \text{SiO}_2 + 3 (\text{Ca Mg, FeO}) \text{SiO}_2$.

In Schweig's extensive series of experiments, starting with a strongly alkaline magma (17.5 per cent. alkali molecules), then adding separately silica, alumina, iron, magnesia, and lime to saturation, and then later adding also silica to saturation with the other oxide, only in case silica is added to saturation do we find analyses which are comparable with any of the rock analyses plotted by Iddings. The inference is suggested that the natural igneous magmas of the alkaline group are always able to absorb all the silica they will take.

When magnesia or iron oxide or alumina is added with the silica the alkali-silica ratio drops only to about 0.15. But the magma is much more capable of absorbing lime, and after saturation with lime and silica the alkali-silica ratio becomes 0.895 and the SiO_2 70 per cent., bring it well into the eutectic belt, which apparently therefore is that of magmas saturated with lime and silica.

All the glasses were cooled as quickly as possible, and no attempt was made to determine the temperatures of solidification. It would be interesting to repeat the experiments and note the latter.

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